Monte Carlo Simulation of Strand Position in CIC Conductor

Kosuke Aoki, Yoshinobu Izumi, Shigehiro Nishijima, Kiyoshi Okuno, and Norikiyo Koizumi

***Abstract*—The strand position in CIC conductor has been calculated three dimensionally by using Monte Carlo method. The 1152 (3 × 4^3 × 6) Nb_3Sn superconducting strands were packed in the conduit. The manufacturing process of CIC conductor was simulated. The six 4th-stage cables were cabled with a spiral tube and then packed into the conduit. The conduit was compressed with the cable to fix the size and the shape. The conduit was compressed from one end and so that the strands were stretched along the axis unevenly. The contact energy between strands and the strain energy in the strands were considered. It was confirmed that the strand positions were changed by compressing the conduit and the obtained strand positions were similar to those in actual CIC conductor.**

***Index Terms*—CIC conductor, Monte Carlo method, stability.**

I. Introduction

The CABLE-IN-CONDUIT (CIC) conductor has been employed in the large scaled superconducting magnets such as CS model or CS insert coil because it has a high cooling capability, high mechanical rigidity and high insulating performances [1], [2]. However, several problems such as AC loss, current imbalance and mechanical disturbances remain unsolved. These problems are closely related to the strand position in the conduit. If the strand position is clarified, a complete discussion concerning three problems could be made. In this work Monte Carlo method calculating the three dimensional strand position has been developed to analyze the stability of the CIC conductor. In this method the cabling process was simulated to obtain the accurate strand position. The strand position will be applied to analysis of the current imbalance, the coupling losses and the stability of the superconducting magnets [3]–[9].

II. Calculation Procedure

The CIC conductor used in CS model coil [1], [3] was simulated in this work. The 1152 (3 × 4^3× 6) of Nb_3Sn superconducting strands were packed in the conduit. The diameter of the strand was 0.8 mm. Fig. 1 shows the initial strand position of the 4th-stage cable (3 × 4^3) for simulating the strand position of the CIC conductor. Four 3rd-stage cables were placed around the origin. Around the center of each 3rd-stage cable, four 2nd-stage cables were placed. Positions of 2nd-stage cables and strands were also decided in the same manner.

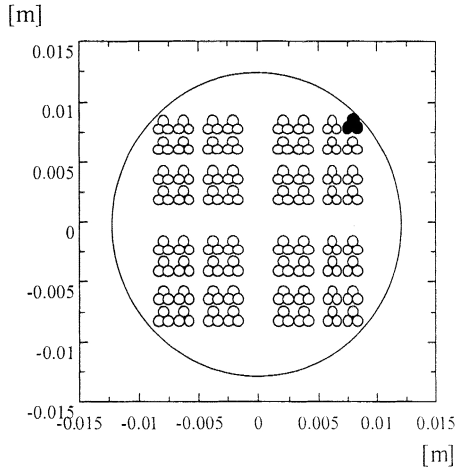

Fig. 1. Initial strand position of 4th-stage cable.

TABLE I
Specifications of CIC Conductor Used for Calculation

Strand		Nb_3Sn
Number of strand		1152
Strand diameter		0.8 mm
Inner diameter of the conduit		38 mm
Diameter of Spiral Tube		12 mm
Cabling pitch	1st-stage	65 mm
	2nd-stage	90 mm
	3rd-stage	160 mm
	4th-stage	270 mm
	5th-stage	430 mm

Each strand was divided into meshes in longitudinal direction at the 1/40 of 4th-stage cable pitch (6.75 mm) to analyze the strand position three dimensionally. The number of meshes was 150 and the length of cable analyzed was 1.0125 m. The strand position is shifted along the conductor because the strands are cabled in clockwise. The each stage cable was twisted independently.The strands were rotated by $\Sigma_k(2\pi iz/L_k)$ where z is mesh length, L_k is twist pitch of kth stage cable and i is mesh number. The 4th-stage cable rotates for $2\pi iz(1/L_4)$ and then the strand rotates for $2\pi iz(1/L_1+1/L_2+1/L_3+1/L_4)$. The initial position of the 4th-stage cable was produced in the method.

Manuscript received August 18, 2002.
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Digital Object Identifier 10.1109/TASC.2003.812878

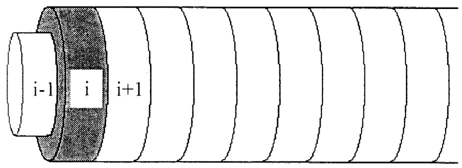

Fig. 2. Schematic illustration of compacting process of cable.

Table I shows the pitch of each stage cable used for the calculation.

In this analysis, the actual cabling procedure was simulated by Monte Carlo method, that is i) compacting the 4th-stage cable, ii) inserting six 4th-stage cable into conduit and iii) compressing the conduit cable. In the compaction process the diameter of the 4th-stage cable reduces to 13 mm. In the inserting process the six 4th-stage cables are cabled and put in the conduit. For fixing the size and the shape, the conduit was compressed. The individual each strand position in compaction, insertion and compression process was determined by Monte Carlo method.

In the Monte Carlo method, the potential energy of the initial position was calculated. Then the strand positions were moved by small distance determined by the random number and the potential energy was calculated. Comparing the potential energy before and after the movement, if the energy after the movement was lower than that before the movement, this strand position was accepted as more stable position. By repeating this procedure, the most stable position was determined. In the compacting and the compressing process, the same procedure was performed to determine the strand position.

The contact energy between the strands, between the strand and the conduit, and between the strand and the spiral tube were considered. They were calculated by using the Hertz's formula. The tensile strain energy of strand was also calculated in the compression process. In the actual manufacturing process, the cables were compressed from one end to another. To simulate the compacting or the compressing process the same process as the actual manufacturing process was simulated as shown in Fig. 2. The compaction was performed considering the tensile energy of strands between $(i-1)$th and ith, and between ith and $(i+1)$th mesh.

III. Results and Discussion

Fig. 3 shows the initial position of the 4th-stage cable in a certain cross section. Fig. 1 shows the initial strand position in the end of the cross section, but in the other cross section as Fig. 3 it is found that the strand positions rotate by the cabling process. Three strands marked black being in the right and upper end come to the position marked black in the same way as shown in Fig. 3. In this phase, three strands keep the position regularly. The cable was compacted to 13 mm in diameter by means of Monte Carlo method.

Fig. 4 shows the position of the 4th-stage cable after compaction. By compaction to 13 mm in diameter little by using Monte Carlo method, the actual compaction process could be simulated. Three strands marked black in Fig. 3 were also compacted and reached to the stable position shown in Fig. 4. The Regulation of three strand positions in Fig. 3 was crumbled by

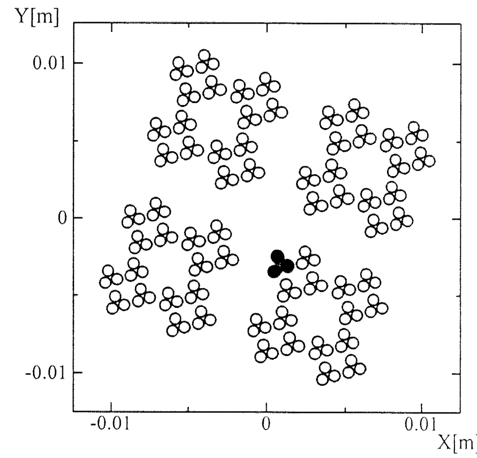

Fig. 3. Initial strand position of 4th-stage cable.

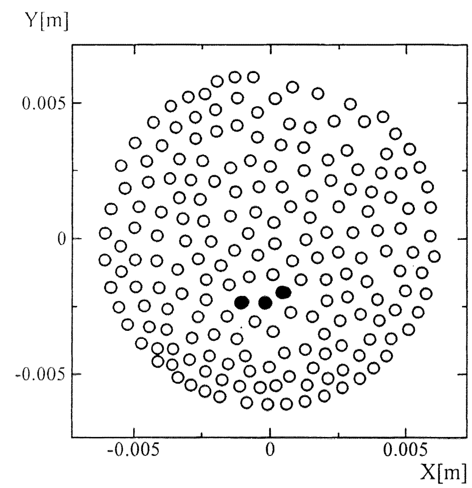

Fig. 4. Strand position in 4th-stage cable after compaction.

compacting. At this time the 4th-stage cable was straight. The 4th-stage cable was rotated by $2\pi iz/L_5$ around the spiral tube placed on the center of the conduit, where L_5 is the pitch of the 5th-stage cable. By considering the periodic boundary condition, the six 4th-stage cables were placed around the spiral tube and the position of the 5th-stage cable was determined. After that, the conduit was compressed to 38 mm in diameter.

The periodic boundary condition was introduced to simulate the CIC conductor which had six 4th-stage cables. One 4th-stage cable was put in the 60° sector area. Both edge of the sector are considered to be connected to simulate six 4th-stage cables.

The three dimensional position of the 1st-stage cable before compacting process for 1m long CIC conductor was calculated and presented in Fig. 5. The position marked in Fig. 3 was arranged for three dimensional strand positions by 150 of mesh numbers in the longitudinal direction. It is found that these are cabled around the spiral tube. This figure also shows the initial three dimensional position similarly.

Fig. 6 shows the three dimensional position of the 1st-stage cable in CIC conductor after compression. It was found that the strand position was changed markedly by the compression. By the compaction and the compression, the turning radius of the spiral shown in x–y plane became to 19 mm in radius, a half

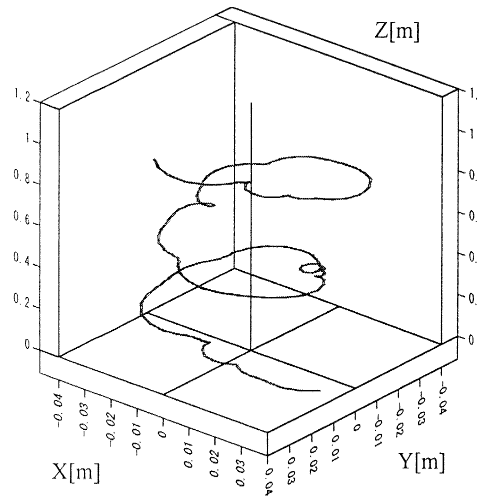

Fig. 5. Strand position of the 1st-stage cable in the CDIC cable after compression.

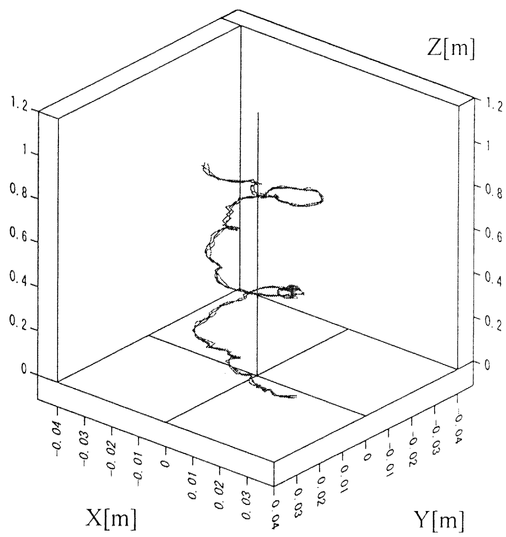

Fig. 6. Strand position of the 1st-stage cable in the CIC cable after compression.

size of that in Fig. 5. Only three strand positions were shown in the figure, but all of the other strand positions of 1152 strands were calculated. By the calculation of three dimensional position, not only the strand position in a certain cross section but also the strand position in the other location that can be seen actually became able to be analyzed. The process was successfully reproduced by this developed method.

Fig. 7 shows the strand position in the cross section after the compression. It was confirmed that the actual strand position can be realized by this method. The position of three strands shown in Figs. 3 and 4 in a 1st-stage cable are marked on this figure. It is found that the regulation of three strand positions in this figure is more crumbled and another strand gets in between strands. This Monte Carlo simulation could three dimensionally determine all of strands position without destruction of conductor. The all strand positions of 150 meshes were calculated. It became possible to analyze the strand position in each

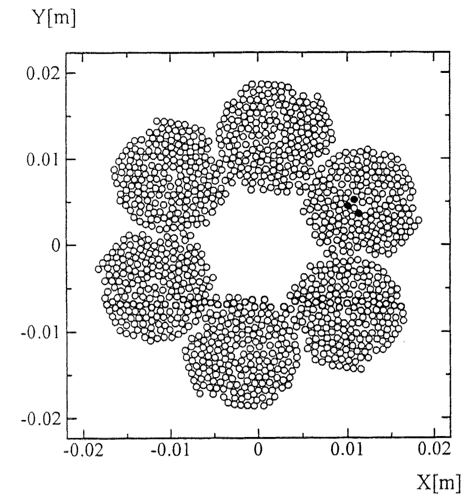

Fig. 7. Strand position of CIC conductor.

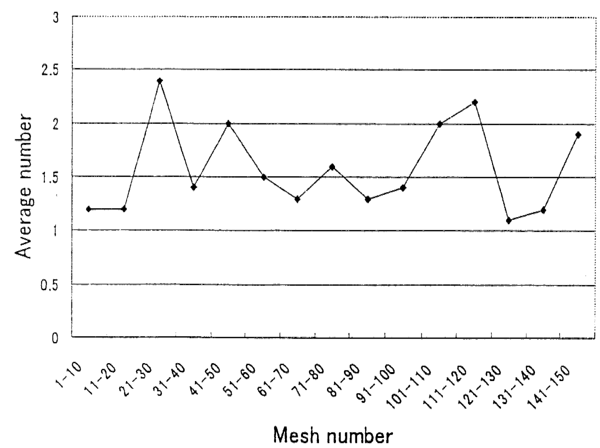

Fig. 8. Number of strands contact with a certain strand.

process. And the strand position in the longitudinal direction and the cross section could be calculated and the strand position in the CIC conductor was analyzed.

By using the calculated strand position various parameters such as contact stress, mechanical disturbances, and AC loss can be calculated [4]. One example of the derived parameter is shown in Fig. 8. This figure shows the number of strands which contact with a certain strand along to the conductor. The number changes with the position. By performing this calculation for the all strands, it can be clarified each part of each strand contacts with the other strands or conduit, and the contact stress can be calculated. Therefore it can be applied to calculating the mechanical disturbances or the AC loss, and it would be linked to the analysis of the stability of the superconducting magnet.

IV. Conclusion

All of the strand position in CIC conductor could be three dimensionally determined without destructing actual conductor by Monte Carlo simulation. By using this calculated strand position, various losses, current imbalance, and mechanical disturbances in the superconducting magnet can be analyzed and the stability of CIC conductor would be discussed.

ACKNOWLEDGMENT

The authors are grateful to K. Okuno and N. Koizumi at Japan Atomic Energy Research Institute for their valuable discussions on CS model coil and CS insert coil.

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